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13. ABSTRACT *(Maximum 200 words)*

A new technology has been discovered. Elastic ties have been introduced into a class of tensegrity structures. Each structure can be stowed or packaged into a cylindrical form with the struts lying side by side. When the structure is released from its stowed position it self-deploys and reaches a position of minimum potential energy. It is considered that one major application of this new technology is the development of novel self-deploying structures for the deployment of antennas in space. This proposal addresses the key theoretical issues which provide a proper basis for the understanding of: (i) the geometrical stability of the structures; (ii) the kinematics and statics of self-deployment from the stowed position to the fully deployed position; (iii) the elastic stability of the structures via application of Catastrophe Theory; (iv) the kinematics and statics of the structures for position control and actuation of the antenna surface using screw theory. The investigators firmly believe that an analysis based properly on the geometry, statics, and kinematics of the structures will lead to optimal designs and performance. This will further lead to reduced costs and a high degree of reliability.

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The Theoretical Analysis of Self-Deployable Tensegrity Structures

Final Report

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1. Introduction

The primary objective of the project was to provide a proper fundamental theoretical study based primarily upon the geometry of lines and screws of a class of tensegrity structures with compliant ties that will self-deploy from a stowed or packaged position Figure 1 shows a simple tensegrity structure comprised of three struts and nine ties Compliance is introduced into the ties to allow the structure to be stowed in a compact volume with the additional benefit that the device will self-deploy to its minimum potential energy configuration (see Figure 2)

This study, which was based solely upon the geometry of the connector lines of in-parallel devices, provides the designer with important up-front information in the first stage of design It essentially provides the designer with the dimensions and relative sizes of the top and base platforms together with their distance apart which optimizes geometrical stability

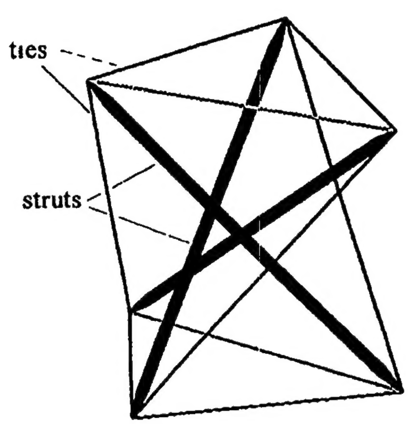

Figure 1 Tensegrity Prism

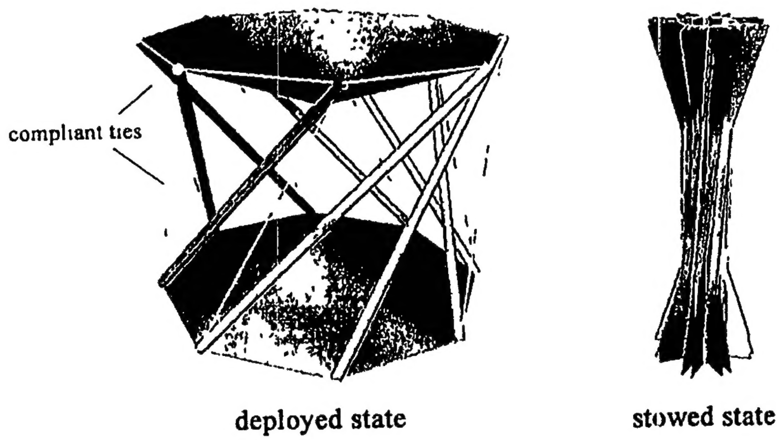

Figure 2 Self-Deployable Tensegrity System

2. Accomplishments

The work that was accomplished under this project is documented via a series of papers and dissertations A brief summary of the major contribution of each work is presented together with a link to the full document

a) Lee, J , "Investigations of Quality Indices of In-Parallel Platform Manipulators and Development of Web Based Analysis Tool", Ph D dissertation, 2000

> The study of tensegrity structures was based on the study of the similarities between these devices and spatial parallel platforms This work provided a thorough analysis of the line geometry of the leg connectors that connect the upper and lower bodies of a parallel platform The optimal geometry that would result in the lines being as far as possible from being linearly dependent was determined This result was significant in that a *quality index* was defined that compares any current state (position and orientation) of the platform to the optimal state

b) Duffy, J , Rooney, J , Knight, B , and Crane, C , "A Review of a Family of Self-Deploying Tensegrity Structures with Elastic Ties " The Shock and Vibration Digest, Vol 32, No 2, Mar 2000, p 100-106

> This paper provided a review of a family of tensegrity structures that self-deploy from a stowed configuration Applications of the technology to the deployment of antennae and space structures as well as to tents and shelters is discussed The paper presents how the family of tensegrity structures evolved from a study of in-parallel platforms with compliant legs or connectors A number of relevant references are cited

c) Stern, I , "Development of Design Equations for Self-Deployable N-Strut Tensegrity Systems," MS thesis, 1999

> This thesis analyzes the internal force organic to n-strut tensegrity systems to obtain a better understanding of tensegrity and develop generic design equations for self-deployable tensegrity systems A static analysis of the internal forces is conducted on the top and bottom platforms of four n-strut tensegrity systems, which determines the geometry of the systems and relationship between the internal forces when at equilibrium This thesis provides a closed-form solution to all the equilibrium positions of a symmetric tensegrity system

d) Knight, B , "Deployable Antenna Kinematics Using Tensegrity Structure Design," Ph D dissertation, 2000

> This work focuses on how tensegrity principles can be applied to the problem of designing deployable antennae for space applications A 6-6 structure was chosen to provide enough radial spars on which to 'hang' the reflective surface of the antenna An improvement to the basic tensegrity prism is presented which adds additional ties These ties substantially improved the stability of the deployed system

e) Knight, B , Zhang, Y , Duffy, J , and Crane, C , "On the Line Geometry of a Class of Tensegrity Structures," Sir Robert Stawell Ball 2000 Symposium, University of Cambridge, UK, July 2000

This paper investigates the line geometries of a family of tensegrity structures which have been called skew prisms It is remarkable that the quality index for each
skew prism is zero, which means that it has instantaneous mobility Further examination revealed that all the sets of connector-lines for each prism belong to a linear complex of lines within a 5-system of screws Each of the sets of lines is reciprocal to a single screw Adding ties along the diagonals of the skew prism faces can easily form reinforced skew prisms

d) Correa, J , "Static Analysis of Tensegrity Structures

- Correa, J , "Static Analysis of Tensegrity Structures," MS Thesis, 2001
- Correa, J , Duffy, J , and Crane, C , "Static Analysis of Tensegrity Structures, Part I Equilibrium Equations," Proceedings of the ASME International Design Engineering Technical Conference, Montreal, Aug 2002
- Correa, J , Duffy, J , and Crane, C , "Static Analysis of Tensegrity Structures Part II Numerical Examples," Proceedings of the ASME International Design Engineering Technical Conference, Montreal, Aug 2002
- Correa, J , Duffy, J , and Crane, C , "Static Analysis of Prestressed Tensegrity Structures," Proceedings of the ASME International Design Engineering Technical Conference, Montreal, Aug 2002

This work addressed the static analysis of tensegrity systems to determine their equilibrium position when external loads are applied The derivation of the mathematical model for the equilibrium positions of the structure is based on the virtual work principle together with concepts related to line geometry The solution for the resultant equations is performed using numerical methods Several examples are presented to demonstrate this approach and all the results are verified

e) Marshall, M , "Analysis of Tensegrity-Based Parallel Platform Devices," M S Thesis, 2003

A new and novel parallel platform that incorporates tensegrity concepts was conceived and analyzed in this work The device consists of a rigid body top platform that is connected to its base by three adjustable length but rigid legs and three connectors comprised of a spring in series with a non-compliant cable The problem analyzed is to determine the lengths of the three rigid legs and the lengths of the three non-compliant cables in order to position and orient the top platform as desired at a user specified potential energy state The significance of the device is that the position and orientation of the top platform can be achieved while at the same time controlling the vibrational properties of the device

f) Knight, B , Duffy, J , and Crane, C , "Optimization of Ring Trusses for Antenna Structures Using Line Geometry," Journal of Spacecraft and Rockets, Vol 40, No 4, pp 565-569, 2003

The line geometry techniques utilized during this project were applied to the analysis of ring trusses that could be used for the design of antenna structures in space These structures incorporate tension ties and as such are related to tensegrity systems A new method for optimizing the ring trusses is presented

g) Bayat, J , and Crane, C , "Closed-Form Equilibrium Analysis of a Planar Tensegrity Structure," submitted to the 9th International Symposium on Advances in Robot Kinematics, Sestri Levante, Italy, 28 June - 1 July 2004

This work aims to develop a closed-form solution to the tensegrity equilibrium problem that was addressed numerically in (d) above The simplest tensegrity mechanism is presented which is formed of two struts and four ties The paper solves the problem where two of the ties are compliant A twenty-eighth degree polynomial solution was obtained which identifies all the cases where the potential energy stored in the springs is minimal (or maximum) Numerical results are presented

3. Conclusion

This report aims to document the body of work that was accomplished under this grant Two specific accomplishments were made First, it is believed that significant advances were made to the basic understanding of tensegrity systems as detailed in the items above Second, a new hybrid mechanism was conceived that incorporates tensegrity concepts to allow for simultaneous positioning and vibration control of the top platform These developments should lead to specific future applications in the areas of space and ground based systems